Hybrid Bias Controller for GaN HEMT Radio Frequency Power Amplifiers

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Abstract— **This work presents the design of a novel hybrid controller topology for the biasing and protection of GaN HEMT transistors in radio frequency (RF) power amplifiers. These high-electron-mobility transistors require dual power supplies with opposite polarities, making their management and protection challenging, particularly when relying on manual sequential biasing. The proposed controller, built on the STM32 platform, optimizes the regulation of transistor temperature, drain-source voltage V_{ds}, and drain current I_d. It ensures precise biasing control and proper sequencing during the power-on and power-off cycles of the RF power amplifier. At startup, an integrated dichotomy algorithm dynamically adjusts the gate-source voltage V_{gs}, enhancing operational stability and efficiency. By improving transistor control and reliability, this approach mitigates rapid degradation, thereby reducing manufacturing costs and accelerating the commercial adoption of GaN HEMT power amplifiers.**

I. INTRODUCTION

With the growth of modern telecommunications systems, both civilian and military, radio frequency (RF) technologies are facing expanding demands for reliability and performance. Moreover, in response to the saturation of low frequencies, the increasing demand for high data rates, and the accumulated power requirements, the use of high frequencies has become essential. In this context, Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) emerge as promising solutions to meet the needs of high-frequency power applications. The GaN HEMT transistors [1] are distinguished by their high-power density, considerable gain, excellent energy efficiency, and their ability to operate at high frequencies, making them components of choice for designing next-generation RF power amplifiers. Unfortunately, these transistors require two supply voltages with opposite polarities, as well as precise synchronization of the turn-on and turn-off phases. A control failure can lead to rapid degradation or deterioration of these transistors, thereby increasing development costs and limiting their commercial adoption. It is in this context that our research work has focused on the design and development of a new hybrid controller topology, specifically created to address the challenges related to the biasing and protection of GaN HEMT transistors integrated into high-power RF amplifiers. This controller, built around an STM32 microcontroller, offers optimized management of the transistor's critical parameters, including temperature and the V_{gs} voltage. It ensures precise biasing and rigorous sequencing during the turn-on and turn-off phases of the high-power RF amplifier. It ensures precise biasing and rigorous sequencing during the turn-on and turn-off phases of the high-power RF amplifier. Thanks to the integration of a dichotomy algorithm [2], it accurately adjusts the V_{gs} voltage applied to the transistor, thereby ensuring optimal performance stability and reliable protection against thermal variations and voltage fluctuations. The performance and reliability of the developed hybrid controller were tested on a high-power RF amplifier using Wolfspeed's CG2H40025F transistor [3], a gallium nitride (GaN) high electron mobility transistor (HEMT). The obtained results confirm the effectiveness of this approach in ensuring optimal biasing and precise sequencing, thereby avoiding any risk of degradation or deterioration of the transistor.

II. BIAS SEQUENCING OF THE GAN HEMT TRANSISTOR

In general, transistors require biasing with V_{gs} and V_{ds} to ensure proper operation. Bias sequencing is the most crucial factor for the DC operation of GaN HEMT transistors [4]. To achieve optimal performance, the startup and shutdown sequencing must be followed as shown in Fig1. the **CG2H40025F**, which is a **depletion-mode (D-mode)** GaN HEMT. This classification is based on the following evidence:

- Threshold Voltage (V_{th}): According to the manufacturer's datasheet (Wolfspeed), the CG2H40025F has a **negative threshold voltage**, typically around **–3 V**, which is a key indicator of a D-mode device.
- Normally-On Behavior: At V_{gs} = 0V, the device conducts a significant drain current, confirming it is a **normally-on** device. To turn the device off, a **negative gate-source voltage** must be applied (this is a typical feature of depletion-mode transistors).

The transistor starts with a negative voltage lower than the pinch-off voltage (e.g., -4V). GaN HEMT transistors can become potentially unstable at lower V_{ds} values if the V_{gs} value is not kept below the pinch-off voltage.

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Biasing sequence of the GaN transistor [5],[6] during startup and shutdown is as follows:

To power-up the GaN Transistor:

- Set the gate-source voltage V_{gs} to the pinch-off voltage V_P, typically -4V,
- Apply the drain-source voltage V_{ds} to the nominal supply voltage 28V,
- Gradually increase V_{gs} until the drain current I_{ds} reaches the specified value 250mA according to the datasheet of the CG2H40025F transistor.

To power-down the GaN Transistor:

- Turn off the RF source,
- Reduce Vgs to V_P, typically -4V,
- Reduce V_{ds} to 0V,
- Disable V_{gs}.

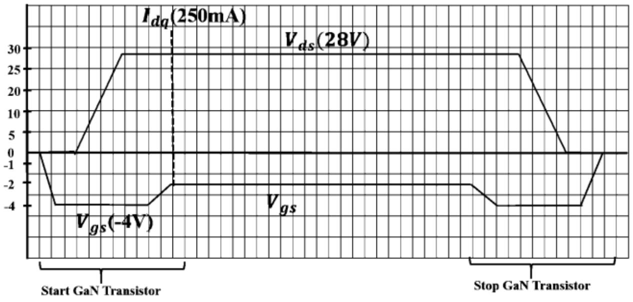

Figure 1: Illustrates recommended power-up and power-down sequences for the drain and gate voltages [7].

III. DESCRIPTION OF THE IMPLEMENTED GaN HEMT HYBRID CONTROLLER

The designed hybrid controller is divided into three main interesting parts.

The following diagram (Figure 2) illustrates the overall architecture of the controller.

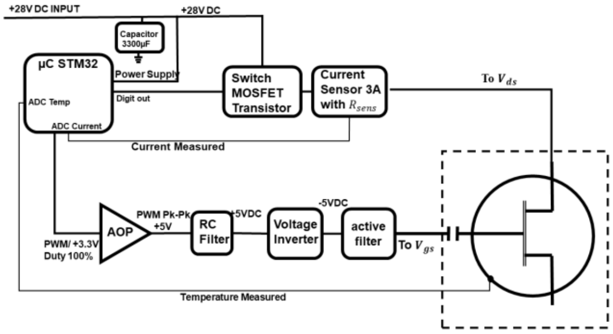

Figure 2: Block diagram of the implemented GaN HEMT hybrid controller.

A. Control of the transistor V_{gs} voltage:

1. Circuit of the transistor VGS voltage controller.

To generate an analog voltage of 2 to 4 V from a PWM (Pulse Width Modulation) signal, we can use a low-pass filter to smooth the PWM signal, followed by adjusting the duty cycle to achieve the desired voltage. Here are the general steps to follow:

- Generation of a PWM Signal: The PWM signal, generated by the STM32 microcontroller (Fig. 3:S3), has an amplitude of 3.3V and a frequency of approximately 70 kHz. However, this amplitude is insufficient to reach voltage levels of 4V or 5V. To address this, an operational amplifier (Fig.3: U11) is used to amplify the signal to a maximum amplitude of 6V. A passive low-pass filter is then applied to smooth the PWM signal and obtain a DC voltage whose value varies according to the pulse width.

$$2V = 6V \times \frac{Duty\_cycle}{100} \tag{1}$$

Duty_cycle= 33.33%

And for a voltage of 4V:

Duty_cycle= 66.66%

- RC Low-Pass Filter: The PWM signal is a square wave that oscillates between 0V and 6V (or the supply voltage). To obtain a filtered voltage, we need to use a low-pass filter to eliminate high-frequency components. A simple RC (resistor-capacitor) filter is usually sufficient. For effective filtering, the cutoff frequency must be much lower than the frequency of the PWM signal.

The cutoff frequency is given by:

$$F_c = \frac{1}{2\pi RC} \tag{2}$$

Where R is the resistance in ohms and C is the capacitance in farads.

In our case, we have chosen a cutoff frequency of 26KHz. R=13Ω and C=470nF (Figure3: R3 and C12).

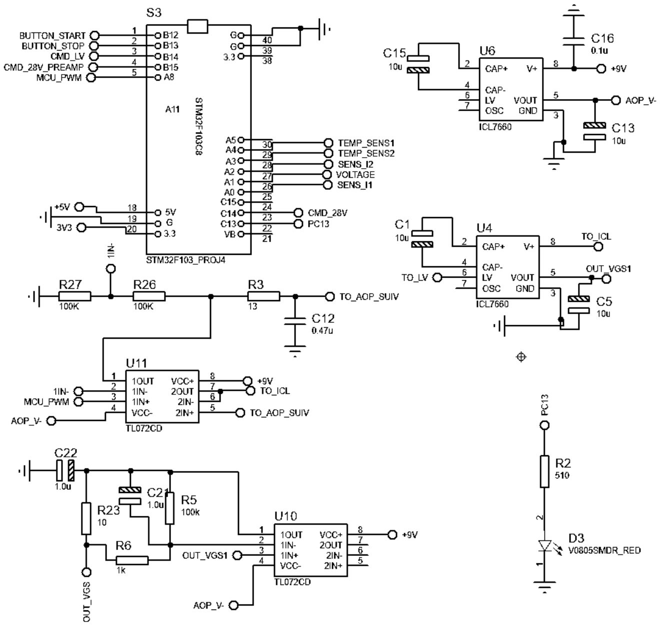

Figure 3: Circuit for controlling the transistor's VGS voltage.

- Voltage Inversion: The voltage at the output of the RC filter powers the ICL7660 circuit [8]. This is a voltage inverter that provides a negative voltage applied between the gate and ground of the CG2H40025F transistor.
- Active Low-Pass Filter: Finally, an active filter (Fig.3: U10) is used for two objectives:
    - Impedance Matching between the ICL7660 Circuit and the RF Transistor Input
    - Filtering of the Output Voltage from the ICL7660 Circuit.

2. *Circuit of the transistor VGS voltage controller.*

Figure 4 presents the dichotomous search (or binary search) algorithm. It is an efficient method for finding the appropriate V_{gs} voltage for the I_{dq} current when the transistor is at rest. The algorithm works by repeatedly dividing the Vgs voltage range [-2V, -4V] into two sub-ranges at each step, gradually narrowing the search interval defined below:

- Initialization**:** Set the values, $V_{gs_{max}}$ and $V_{gs_{min}}$, representing the range of variation for V_{gs}.

$$V_{gs_{min}}=-4\text{V and } V_{gs_{max}}=-2\text{V} \qquad (3)$$

- $V_{gs_{middl}}$**:** Calculate the central value of the interval $[V_{gs_{min}}, V_{gs_{max}}]$:

$$V_{gs_{middl}} = \frac{V_{gs_{max}} + V_{gs_{min}}}{2} \qquad (4)$$

Measure the value of the current Id corresponding to the voltage $V_{gs_{middl}}$.

- Comparison :
    - If the measured current value at the voltage $V_{gs_{middl}}$ is equal to the desired value (250mA in our case), we can stop the search.
    - If the current measured at the midpoint of the interval ($V_{gs_{middl}}$) is smaller than the desired current, it means the desired value is in the left half of the interval, so we update the voltage $V_{gs_{min}} = V_{gs_{middl}}$.
    - If the current measured at the midpoint of the interval ($V_{gs_{middl}}$) is greater than the desired current, it means the value is in the right half of the interval, so we update the voltage $V_{gs_{max}} = V_{gs_{middl}}$.
- Iteration: We repeat the two steps ($V_{gs_{middl}}$, comparison) until the current is found or the value of $V_{gs_{min}}$ exceeds $V_{gs_{max}}$ (indicating that the current is not found).

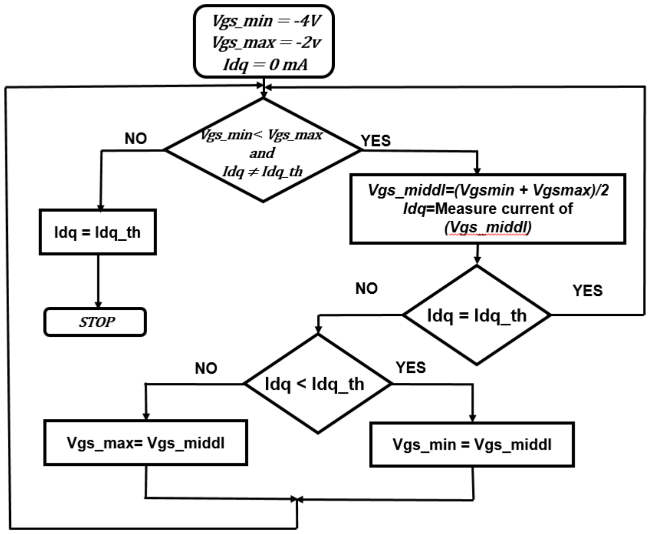

Figure 4: Binary search Algorithm

B. *Control of the transistor Control of Drain current consumption.*

Managing current consumption in this circuit requires a variety of strategies, including bias control, the implementation of current regulators, and the integration of suitable thermal devices. The choice of method is determined by the circuit's specific design parameters and the desired RF performance outcomes.

The use of a current sensor based on a measurement resistor (called R_{sens}) is a common and effective method for monitoring current consumption in a circuit. This sensor works by measuring the voltage drop across the resistor, which is directly proportional to the current passing through it.

Figure 5 shows the circuit diagram for current measurement using the MAX471 current sensor, which has an integrated resistor (R_{sens}).

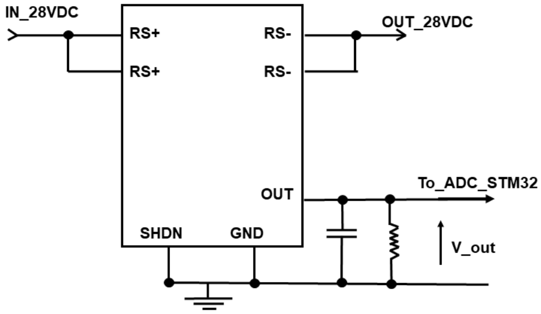

Figure 5 :Id current Measure circuit (MAX471) [9].

One component of the STM32 is configured to monitor the current consumption of the RF power amplifier and take proactive action in case of overconsumption, to protect the RF transistor. It features a real-time monitoring system with a threshold tailored to each specific application. I have configured the STM32 microcontroller to utilize a watchdog with a control window, which tracks the current status within a specified time frame. If the current exceeds the defined threshold during this window (indicating abnormal overconsumption), the watchdog immediately activates a safety measure, such as shutting down the system or reducing the load. This strategy minimizes the risk of damage from current overloads.

When the transistor exceeds the current range set within the watchdog window., an interrupt will be triggered to execute the transistor shutdown sequence, and a LED signaling a current overconsumption fault will be illuminated.

A. CONTROL OF THE TRANSISTOR TEMPERATURE.

The use of a temperature sensor to control a GaN RF HEMT typically requires an approach where the sensor monitors the transistor's temperature and sends this information to the controller to adjust the transistor's operating parameters accordingly.

The temperature compensation function in the GaN HEMT biasing circuit works by adjusting the gate voltage to maintain a stable drain current despite temperature variations. Here are the key elements of the operation:

- Temperature Probe: An NTC10K temperature probe (Fig.6) is used to measure the temperature. It should be placed as close as possible to the transistor to ensure accurate temperature measurement [10].
- Feedback loop: The probe is directly connected to the STM32 microcontroller. This allows the circuit to monitor the temperature and, accordingly, adjust the gate voltage in real-time.
- Temperature coefficient: Typically, for Cree GaN HEMT transistors, the gate voltage must be adjusted by about 0.4 mV per degree Celsius to maintain a constant drain current. The circuit configuration allows for the adjustment of this temperature coefficient [11].

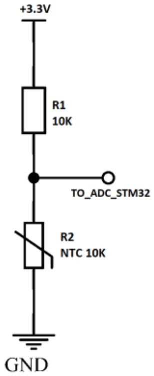

Figure 6 : Circuit for the transistor temperature measurement probe

During the startup of the RF transistor, its temperature increases. Since the variation in the Id current depends on the temperature at a rate of 0.4 mV/°C [11], the programming function implemented in the microcontroller records the transistor's initial temperature (immediately after startup) using the NTC10k probe [10]. It then calculates the appropriate V_{gs} voltage for the I_{dq} current.

When the transistor begins amplifying the RF signal, a temperature compensation function adjusts the PWM signal's duty cycle based on the temperature difference (initial and current temperature). It then updates the V_{gs} voltage to ensure adequate current consumption in V_{ds}.

II. CHARACTERIZATION THROUGH MEASUREMENT OF THE IMPLEMENTED HYBRID CONTROLLER.

The characterization of the hybrid bias controller for GaN HEMT transistors was carried out through a series of experimental measurements aimed at evaluating its performance in terms of accuracy, stability, and speed. The tests on the Electronic board shown in Figure 7 included analyses in both static and dynamic regimes, allowing validation of the controller's ability to maintain an optimal biasing point under various operating conditions. The results confirm the effectiveness of the hybrid approach, combining analog and digital techniques, in improving the reliability and performance of systems based on GaN HEMT transistors.

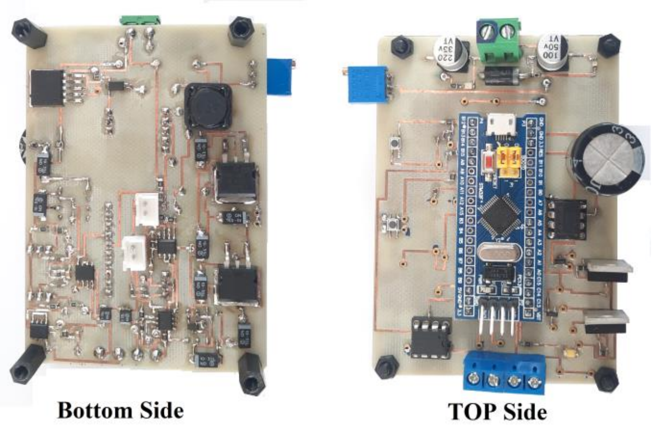

Figure 7: Electronic board of the implemented hybrid controller.

This electronic board is assembled using through-hole components and modules, such as the STM32 board, for laboratory testing. Therefore, it can be miniaturized to achieve a smaller size than the one shown in Figure 7.

The terminal block, highlighted in blue in Figure 7, has four outputs: V_{gs}, GND, V_{ds}, as well as a 28V power supply for the pre-amplifier located upstream of the power amplifier. This setup ensures that the power level is ready for amplification. Using this output, we can control the pre-amplifier (turn it on or off) and follow the proper transistor shutdown sequence (powering up or down the power amplifier), while also preventing the reflected wave phenomenon on the pre-amplifier during transistor shutdown.

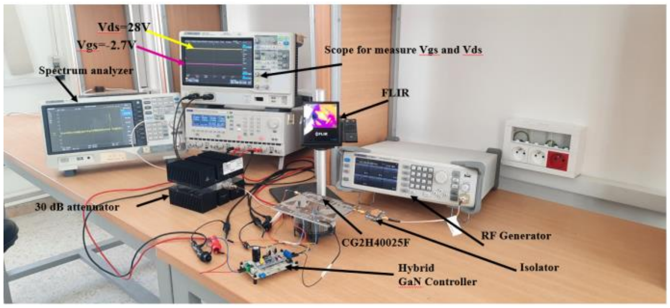

Figure 8: Test Bench for the GaN Controller.

The test bench shown in Figure 8 validates the controller's performance for a 25 W GaN transistor under real operating conditions. Using this bench, we systematically identified the weaknesses and gaps in our GaN controller and adjusted the parameters to optimize the final system's performance and reliability. The results obtained will provide crucial insights for integrating the GaN controller with other GaN transistors in high-power applications.

The experimental setup included:

- A Frequency generator [12] to generate an RF signal within the amplifier's band.
- A Power amplifier made with a CG2H40025F RF transistor [3].
- A Spectrum analyzer [13] to display the amplification results
- An Oscilloscope [15] to observe the changes in voltage levels for V_{gs} and V_{ds} during the transistor's power-up and power-down states.
- A FLIR camera [14] helped us to show the temperature of the RF transistor and all components in the board during the tests.

III. CONCLUSIONS.

In this work, we developed and tested a new hybrid controller topology dedicated to the biasing and protection of GaN HEMT transistors used in RF power amplifiers. This controller, based on the STM32 platform, integrates a dichotomy algorithm to quickly determine the appropriate Vgs voltage for the transistor's Idq current at startup.

The developed controller enables automatic, precise, and reliable management of critical parameters such as temperature and V_{gs}voltage. Experimental results obtained on an RF power amplifier based on the Wolfspeed CGH40025F transistor demonstrate the effectiveness of this approach in ensuring optimal biasing and proper sequencing, thereby minimizing the risk of transistor degradation or damage.

This solution significantly enhances the stability and reliability of GaN HEMT-based RF power amplifiers. The hybrid controller represents an important step toward the broader and more cost-effective adoption of this technology in RF power amplification applications.

As future work, we plan to add a module to the proposed GaN controller board that disconnects the RF signal from the source before initiating the transistor shutdown sequence. This modification will also protect the RF source from any reflected signals.

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